A STUDY OF THE RELATIONSHIP BETWEEN ELECTROMYOGRAPHIC ACTIVITY OF MUSCLES OF THE THIGH AND TOTAL FORCE DEVELOPED BY CYCLING SUBJECTS

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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by

John Anthony Martin

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Thesis Advisor: D. E. Neil

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Subjects were required to pedal a bicycle ergometer (ergocycle) while simultaneous dynagraph recordings were made of

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the EMG of the thigh muscles of the right leg and the calibrated output of strain gages mounted on the right ergocycle pedal. Data from the recordings were analyzed using the BIMED02R computer program developed by the Health Sciences Computing Facility at U.C.L.A., to determine the correlation between EMG and force output, and to determine the interrelationships of all variables by means of stepwise linear regression was performed by the computer program. Trans-generation of variables (EMG) performed in an attempt to examine the possibility of achieving a linear relationship.

Results of this experiment are an initial effort to explore the possibility of developing a reliable, reproducible model with which to accurately describe the complicated inter-relationships which exist during the operation of the human leg. Future efforts of this type should be undertaken to provide a sound basis for advancing the field of powered prosthetic equipment for disabled persons.

A Study of the Relationship Between Electromyographic Activity of Muscles of the Thigh and Total Force Developed by Cycling Subjects

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ABSTRACT

The objective of this thesis was to determine the nature of the relationship between force developed by the human leg and the electromyographic activity (EMG) developed in selected muscles of the lower limb.

Subjects were required to pedal a bicycle ergometer (ergocycle) while simultaneous dynagraph recordings were made of the EMG of the thigh muscles of the right leg and the calibrated output of strain gages mounted on the right ergocycle pedal. Data from the recordings were analyzed using the BIMED02R computer program developed by the Health Sciences Computing Facility at U.C.L.A., to determine the correlation between EMG and force output, and to determine the interrelationships of all variables by means of stepwise linear regression was performed by the computer program. Transgeneration of variables (EMG) performed in an attempt to examine the possibility of achieving a linear relationship.

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I. INTRODUCTION

The preponderance of efforts to date in investigating the relationship between electromyographic (EMG) activity of muscles and corresponding power output have been centered on the upper extremities. Experimental work has been conducted primarily under stringently controlled conditions, and, with the exception of the efforts of Neil [1971], Neil *et al* [1972], Vredengregt & Koster [1968], and Harrison [1963, 1970], those conditions were exclusively either isometric or isotonic, and no efforts were made to study dynamic relationships.

Work by Wilkie [1950] reflected an early effort to use controlled movements in order to quantify certain aspects of muscle movements for accurate reproduction, based upon fixed force-velocity relationships in contraction against different types of loads. Unexplained difficulties were encountered when movements became too complex for application of the mathematical analysis techniques used. A means of applying static results to predictions of dynamic performance was not found.

Bigland & Lippold [1954] attempted to determine a relationship between EMG and a voluntary isotonic contraction of muscles, but were hampered by lack of control of velocity of movement, although they did find that at constant (including zero) muscle velocity, electrical activity was directly proportional to tension exerted. When the rate

of contraction was kept constant, a linear relationship was found to exist between electrical activity and the weight being lifted. Suggs [1969] found a linear decrease in work done per muscle stroke as speed of muscle movement increased.

Efforts have been made to apply results obtained under static conditions to dynamic situations. Kroemer [1970] introduced a procedure for predicting dynamic performance on the basis of static strength tests. Finley [1966], Wagman & Pierce [1969] and Wilson [1969] have sought to stimulate interest in research toward uses of EMG activity for the purpose of powering or controlling prosthetic devices. Hallahan [1973] and Hood [1972] conducted experiments in which some degree of success was obtained in attempting to operate equipment by consciously controlling EMG activity, though both indicated that more research effort would be required to provide meaningful applications.

Both Wilkie [1950] and Vredenbregt & Koster [1968] noted a delay between the beginning of EMG activity and the actual initiation of mechanical action, which Vredenbregt & Koster [1968] observed as being approximately 20 milliseconds, based upon research under both static and dynamic conditions. Basmajian [1967] has investigated activity of selected muscles under flexion and other movements. His findings and those applicable functional descriptions contained in reference 4 were used as the basis for selection of muscle groups to be examined in this study.

As noted by Neil [1971], power may be more appropriate than either force exerted or velocity of movement when

looking for a suitable variable associated with EMG during dynamic contraction, but force exerted had to be selected as the measure in this experiment because of constraints imposed by equipment and time limitations, as well as the lack of precedence in the study of the lower extremities under the dynamic, relatively uncontrolled conditions employed in this experiment. Procedures used in this experiment are, for the most part, an outgrowth of the interest displayed by Neil in the work done on study of the upper extremities and the belief stated by Finley [1966] and Wilson [1969] that a proportional relationship does exist between EMG and force output of muscles.

The objective of this research effort then, is to conduct experiments upon the human leg under purely dynamic, relatively uncontrolled conditions, in order to determine which of the tested muscle groups might serve as reliable predictors of force to be obtained from the leg, and to develop an analytical model to explain EMG behavior or predict force output of the leg on the basis of EMG activity alone. It is preferable that separate accounting for such factors or variables as delay between EMG initiation and muscle activation or series elasticity not be required, but should be accomplished through use of such a model without the requirement for complicated measurements. It is the author's intention to avoid the necessity for conversion from static to dynamic situations, as was espoused by Lippold [1967] by developing a general model based upon

dynamic results, which can be used without the need for interpretation or conversion.

II. METHODOLOGY

A. APPARATUS

1. Equipment

Standard, commercially available equipment utilized was as follows:

1 (8 channel capacity) Dynagraph Recorder, with the following ancillary equipment:

- 5 Preamplifiers
- 3 Dynagraph Amplifiers (2 channels each)
- 4 EMG Couplers
- 1 AC Coupler

1 Bicycle Ergometer (Ergocycle)

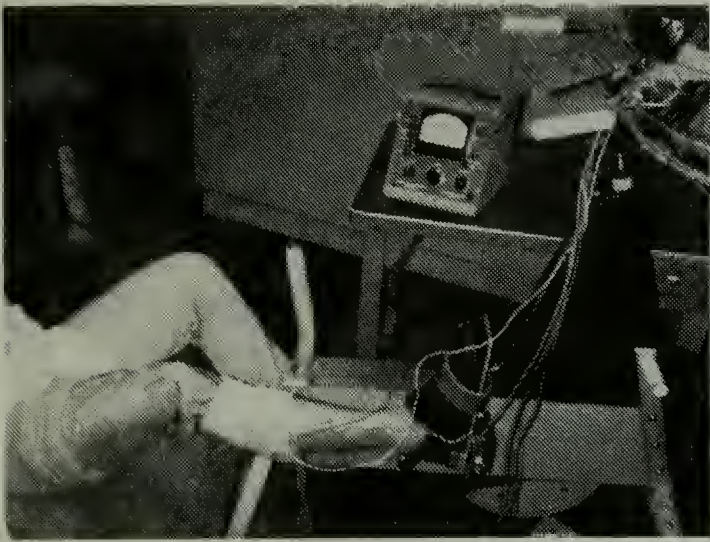
3 Resistance Strain Gages

4 Skin Biopotential Electrode Kits (3 electrodes in each).

Two locally fabricated items were:

(1) A metal seat to permit subjects to sit behind the ergocycle with their hips at the same height as the crank spindle (see Figure 1). The seat was capable of continuous adjustment both fore and aft to accommodate varying leg lengths.

(2) See Figure 2. Two accelerator type adapter pedals were fashioned out of metal for the purpose of forcing the subjects to pedal only with the heel of their foot. Previous data collections during trial runs revealed that this minimized the influence of lower leg muscles on the force developed. The front surface of the right pedal



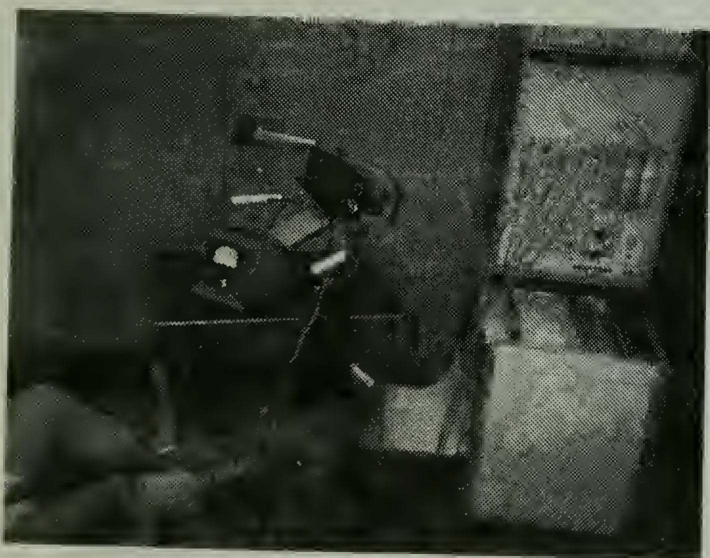
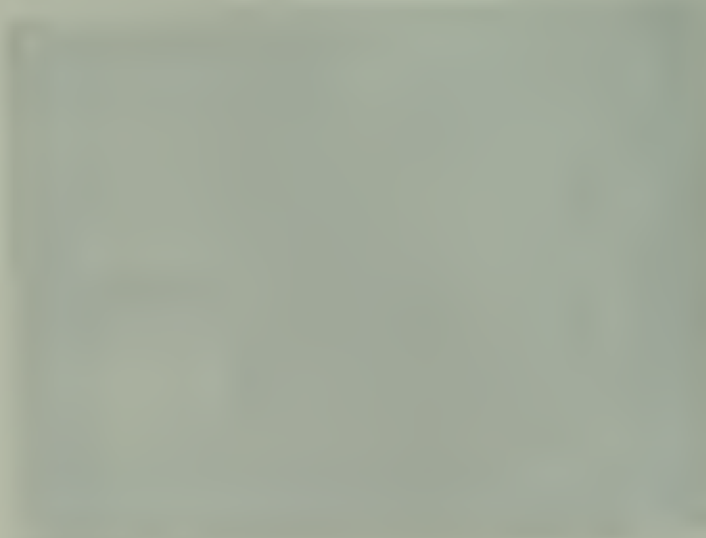


Figure 1. Equipment Layout.



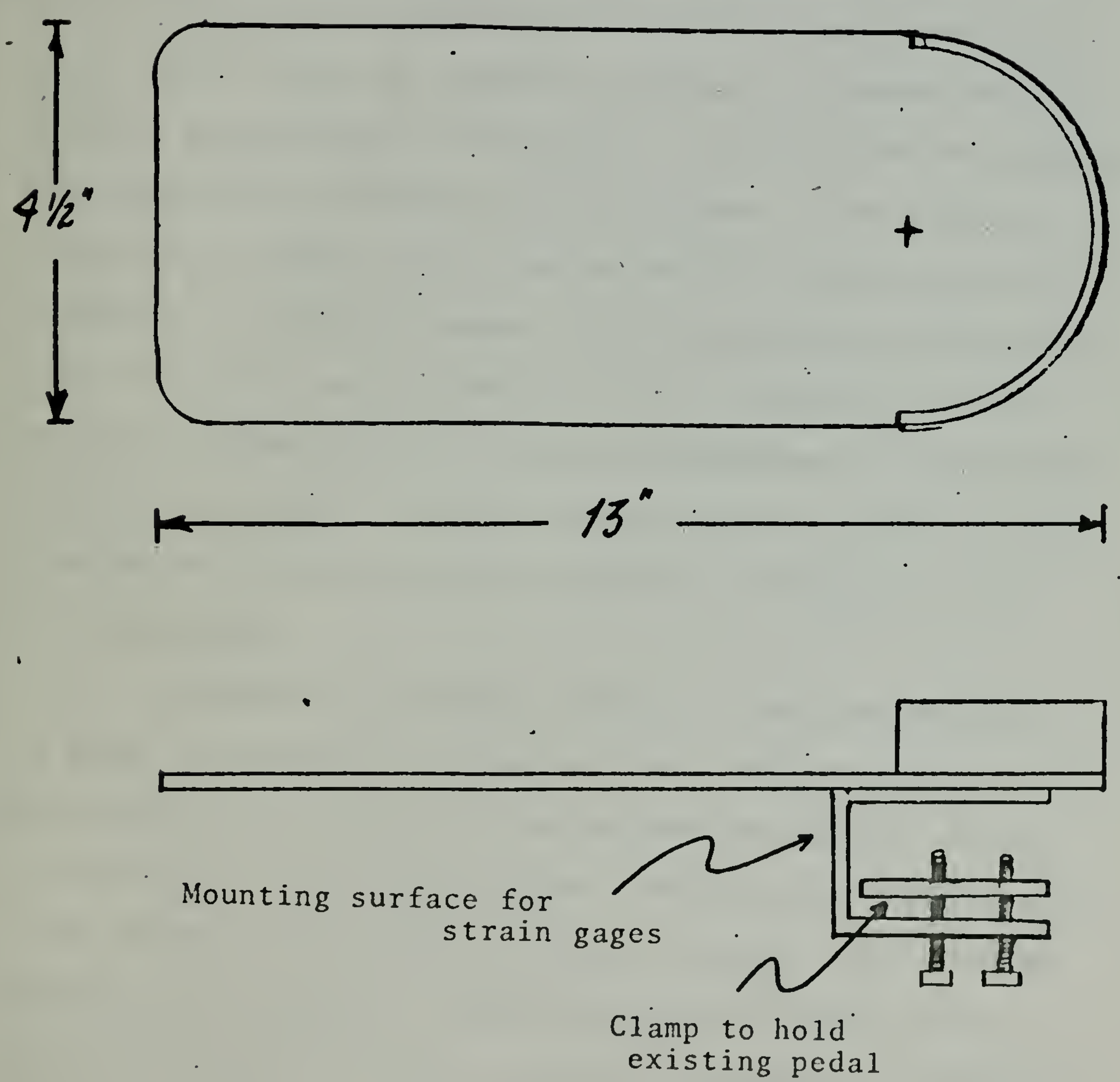


Figure 2. Pedal Design.

provided the surface on which the strain gages could be mounted.

Plastic bridges were fabricated to maintain a constant 2 inch separation between pairs of active electrodes to eliminate any variability in data due to their relative positions. Strain gages were calibrated with the dynagraph recording equipment to insure establishment of a linear scale for the accurate measurement of force levels. Due to the difficulties encountered in obtaining a true zero force point after the subjects feet were strapped into the pedals, an arbitrary (and common) zero point was established and maintained throughout the experiment. The point was located in a manner such that no negative forces were encountered. Adequate compensation for the fact that direction could thus not be identified was made when the data was later separated into separate categories of thrusting (pushing the pedal with the instrumented leg) and recovery (pushing with the other leg) portions or phases of the cycling motion.

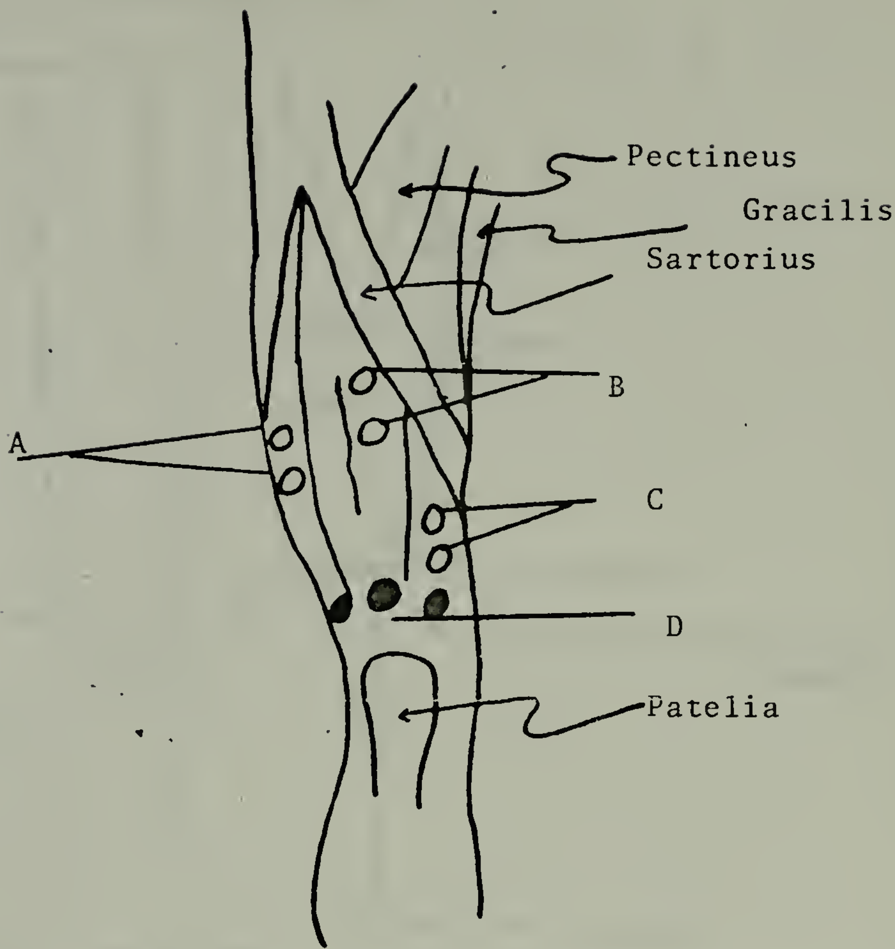
Dynagraph recordings made on 5 separate channels of graph paper provided simultaneous, continuous plots of EMG activity in the four selected muscles and the concurrent output of the strain gages (coupled in a bridging circuit) mounted on the right ergocycle pedal. The recorder automatically placed a timing mark on the paper at one second intervals to insure accuracy in measuring intervals between data points.

2. Subject Preparation

Subjects used were male students in the Naval Postgraduate School, all in the age group 28-36 years, and possessed no known physical handicaps. They received no remuneration for their services, but rather services in kind as a subject for their respective theses.

Prior to conduct of the experiment, each subject was briefed on the purpose and procedure to be employed, but received no feedback information as to his performance relative to experimental goals or to other subjects which preceded him. Before the skin electrodes were attached, the affected areas of the thigh were prepared in accordance with the recommendations of the manufacturer of the bio-potential skin electrodes and the recording equipment. Each subject first vigorously scrubbed the skin on his right thigh with abrasive soap, then thoroughly rinsed with isopropyl alcohol to remove stubborn oils and soap residue. The thigh was then permitted to air dry. Locations for placement of electrodes were thoroughly scrubbed by the author with electronic paste to enhance conductivity of the skin. After being permitted to air-dry, all residue was scrubbed off with paper toweling.

Cups of the electrodes were hen filled with electronic conducting jelly and attached to the skin by means of disposable, double-sided adhesive collars, reinforced with paper masking tape. Sites for placement of the electrodes are indicated on Figures 3 and 4. Active electrodes



Right leg (anterior view)

A. Active electrode placement on VASTUS LATERALIS

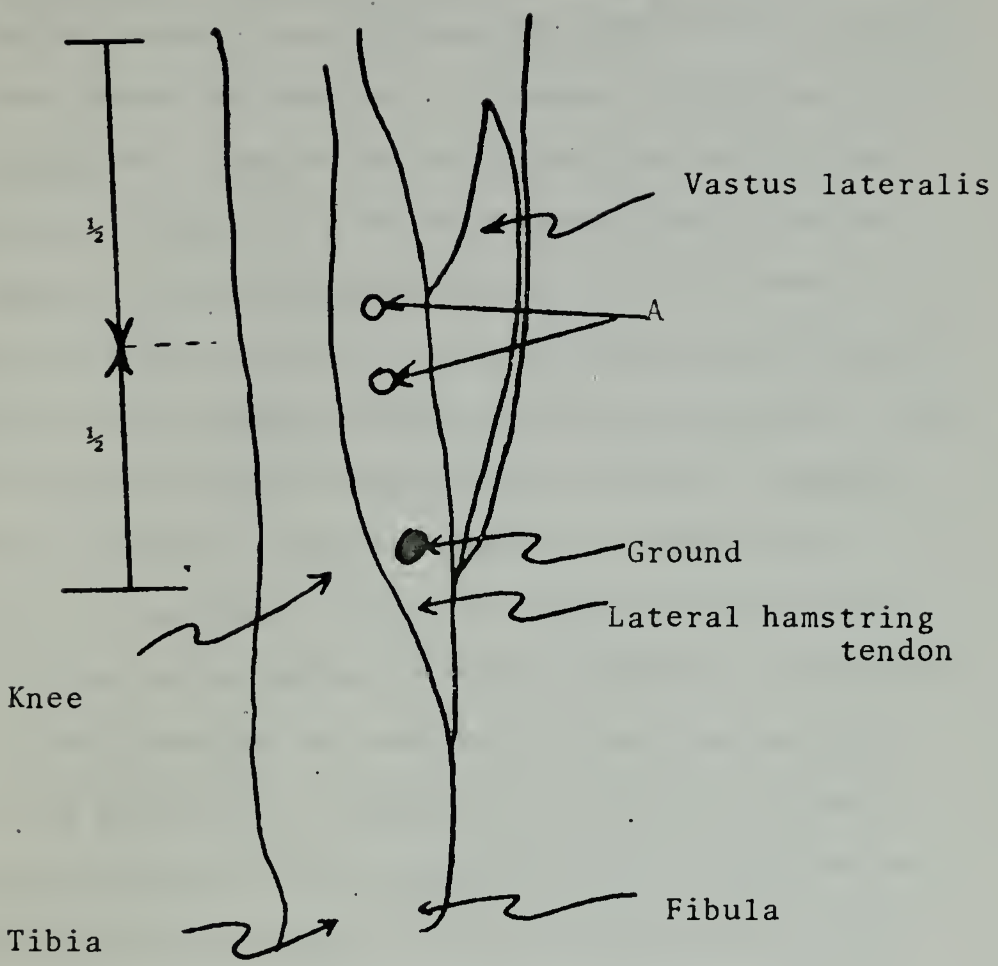
B. Active electrode placement on RECTUS FEMORIS

C. Active electrode placement on VASTUS MEDIALIS

● Ground

D. Area of tendon of QUADRICEPS FEMORIS

Figure 3. Electrode Placement (Anterior).



Right leg (posterior view)

A. Active electrode placement on BICEPS FEMORIS

Figure 4. Electrode Placement (Posterior).

were placed distally over the middle of the exposed portion of the muscles.

3. Experimental Procedure

The experiment was designed to continuously record data on force developed during all phases of cycling on a bicycle ergometer. Data to be extracted for further processing would be limited to those segments during which a steady state of force production existed in the manner advocated by Harrison [1970]. A special seat was designed and methods of instrumentation were developed during "trial and error" processes over a period of 6 months. Seating was considered to be a critical factor in view of the desirability of reducing influence of other parts of the body on the outcome as noted by Wilkie [1950]. The use of bipolar instrumentation was decided in order to increase the effective muscle area within the sphere of influence of an active electrode, while minimizing the contribution of unwanted adjacent muscles. By this action, some risk of signal cancellation, damping and/or summation was accepted, as discussed by Sidowski [1966]. Loads imposed were minimal, both to reduce the possibility of fatigue and to achieve virtually the same accuracy with surface electrodes as would be possible with imbedded electrodes, according to Bigland and Lippold [1954].

Locations for placement of electrodes were determined by first compiling a list of muscles whose functions were related to the production of a cycling motion, in the

publication by Gray [1970]. The list was reduced by eliminating those muscles which were either not accessible by surface electrode or were too small for accurate placement of the electrodes without overlapping adjacent muscles.

Each subject was told to maintain a pace of approximately 60 RPM, and was provided with a tachometer to give him continuous feedback as to his performance in this regard. This speed had been selected through previous trials conducted to determine the most comfortable pace for an experiment of this nature and duration (9 minutes).

A total of 16 groups of data points were taken on each subject. The ten data points in each group were taken at one second intervals. Care was taken to insure that the groups did not cover periods of time when the subjects were in the process of making a transition between load levels. During the course of the nine minutes in which they were required to pedal, the ergocycle automatically progressed through nine different increasingly difficult load levels. Load and no-load periods were changed at 30 second intervals, with the exception of one 150 second load period of intermediate difficulty.

EMG activity was measured as the positive amplitude of the measured signal. This was recorded in a scale which was convertible to millivolts of potential. Corresponding force output of the strain gages was recorded in a scale which was directly readable in pounds above the arbitrary zero point.

4. Statistical Techniques

Statistical techniques employed to reduce the data and provide the desired analysis of relationships and production of the final models were those of correlations and stepwise linear regression. Transgeneration of variables was accomplished to enhance the multiple R value obtained when the linear relationship was observed to fail.

The computer program selected was the 17 July 1970 version of BIMEDO2R, developed by the Health Sciences Computing Facility at U.C.L.A. In all uses of the program, the default values for required F values were used (e.g., F value for inclusion was .01, F value for deletion was .005).

B. RESULTS

Analysis of the linear regression program revealed a high variability in performance between subjects. Though improvement in overall relationships resulted when data were separated into phases of thrusting (instrumented leg actively pushing) and recovering (other leg pushing), the linear "fit" obtained was less than satisfactory, and failed to strongly support the existence of a linear relationship between force output and EMG activity of the tested muscle groups under the dynamic, relatively uncontrolled conditions of this experiment.

The linear model developed by the use of the computer program is one which yields a value for force output in pounds when the products of muscle EMG (measured in millivolts

of potential) and their respective modifying coefficients are summed and are all added to a constant value which is applicable under the specific condition or phase of cycling. The mathematical model can be expressed as:

$$Y_j = \alpha_j + \sum_i X_i,$$

where,

Y_j represents the force output for configuration j

α_j represents the constant force value associated with configuration j

X_i represents the EMG activity in the i^{th} muscle group.

Efforts to enhance the values of R obtained through use of the above model were made by transgenerating the variables (EMG), using the capabilities of the BIMEDO2R program. The model which resulted modifies the above linear model by generating a different constant value and adding an additional factor in the model (the transgenerated variable). The mathematical model can be expressed as:

$$Y_k = \alpha_k + \sum_i X_i + \sum_i (\beta X)_i,$$

where,

Y_k represents the output force for configuration k

α_k represents the constant force value associated with configuration k

X_i represents the EMG activity in the i^{th} muscle group

$(\beta X)_i$ represents the transgeneration of variable i.

The outcomes of the linear regression and transgeneration programs are contained in Tables I and II, respectively. A negative coefficient reflects the effect of an opposing muscle group. A zero coefficient indicates that the variable (muscle group) is not present in the equation because of an insufficient F value for entry in the regression model. (F to enter was .01, F to remove was .005.)

Configuration	Constant	Multiple R	R^2
1 (full cycle)	18.59807	.3007	.09042
2 (thrust only)	17.72839	.3506	.12292
3 (recovery only)	20.14877	.3497	.12229

Configuration	Muscle Group	Coefficient	Standard Error	Correlation with Force
1 (full cycle)	Biceps Femoris	1.90817	0.39675	0.169
	Vastus Medialis	-0.80168	0.21661	-0.018
	Rectus Femoris	-0.38364	0.28308	-0.043
	Vastus Lateralis	2.37037	0.36572	0.190
2 (Thrust)	Biceps Femoris	1.95201	0.56301	0.179
	Vastus Medialis	-0.55809	0.28460	0.067
	Rectus Femoris	0	N/A	0.060
	Vastus Lateralis	2.80016	0.55217	0.270
3 (Recovery)	Biceps Femoris	1.57208	0.59651	0.118
	Vastus Medialis	-2.47163	0.41895	-0.282
	Rectus Femoris	-0.41992	0.34755	-0.157
	Vastus Lateralis	1.54056	0.47697	0.049

Table I. Results of Regression Analysis of Force versus EMG.

Configuration	Constant	Multiple R	R^2
1 (Full cycle)	18.2867	.4046	.16370
2 (Thrust)	15.09449	.4739	.22458
3 (Recovery)	16.59225	.3619	.13097

Configuration	Muscle Group	Coefficient	Standard Error	Correlation with Force
1 (Full cycle)	Biceps Femoris	2.81334	0.83195	0.1690
	Vastus Medialis	-3.45561	0.46444	-0.018
	Rectus Femoris	-0.34857	0.42706	-0.043
	Vastus Lateralis	3.16325	0.58528	0.190
	$(\text{Biceps Femoris})^2$	-0.16891	0.15297	0.134
	$(\text{Vastus Medialis})^2$	0.26223	0.03959	0.086
	$(\text{Rectus Femoris})^3$	0.01321	0.01110	0.026
	Log_{10}(Vastus Lateralis)	-2.00789	1.49914	0.098
2 (Thrust)	Biceps Femoris	0	N/A	0.179
	Vastus Medialis	0.80135	0.41173	0.067
	Rectus Femoris	1.06370	0.75883	0.060
	Vastus Lateralis	3.23937	0.97891	0.270
	Log_{10}(Biceps Femoris)	6.53655	1.36878	0.248
	Log_{10}(Vastus Medialis)	-8.20536	1.96685	-0.084
	Log_{10}(Rectus Femoris)	-2.66855	2.02865	-0.024
	Log_{10}(Vastus Lateralis)	-1.60082	2.78068	0.187
3 (Recovery)	Biceps Femoris	2.55564	1.01180	0.118
	Vastus Medialis	2.32958	0.5933	-0.282
	Rectus Femoris	-0.08762	0.61774	-0.157
	Vastus Lateralis	2.24995	0.75519	0.049
	Log_{10}(Biceps Femoris)	-2.22054	1.64598	0.048
	Log_{10}(Vastus Medialis)	0.26838	1.23583	-0.213
	Log_{10}(Rectus Femoris)	-1.13937	1.47851	-0.186
	Log_{10}(Vastus Lateralis)	-2.25004	1.78473	-0.033

Table II. Results of Transgenerations of Force versus EMG.

III. DISCUSSION/CONCLUSIONS

The greatest divergences from expected results were the lack of agreement between subjects as to relative contributions of muscle groups in the prediction of force output, as reflected in the individual data analyzed early in the experiment, and the overall significant reduction in the value of multiple R which was experienced when individual data cards were combined for final regression analyses.

Failure to achieve the desired degree of "fit" during linear regression, as evidenced by the unsatisfactory value of multiple R achieved during exercise of the BIMEDO2R computer program, could have resulted from any number of factors. The effects upon data purity of improper placement of instrumentation or the impact upon analytical difficulties of the design decision to avoid at all costs the necessity to consider such complicating factors as series elasticity effects on an individual basis are, at this point, impossible to determine. The desirability of retaining simplicity in the number of necessary inputs to a model remains, but results of this experiment may point towards the necessity of developing a more complicated relationship. In future efforts to conduct such an experiment it may be necessary to constrain the sidewise movement of the subjects knees, thereby diluting the relative freedom of the manuever, in order to determine if this will improve the relationship, as expected by the author. Additionally, from the outset

of the experiment, one experimental goal might advisably be to develop purely individual relationships, in lieu of clinging to some effort to consolidate the data to permit development of a broad, general model.

A definitive relationship between EMG activity of the four selected muscle groups and the force output measured at the heel during a cycling task could not be determined. The results obtained from this, and any similar experiment are by their very nature task-oriented, and could not be expected to apply in all situations. Just from the standpoint of the field of powered prothesis alone, sufficient need for this type of data, when it can be adequately defined in workable terms, exists to justify continued efforts to isolate those variables and factors which combine to perform the amazing functions performed by a single, "simple" human leg. There exists a need to conduct experiments of this general type, and further to conduct them in such numbers and in such depth as to provide an opportunity to examine those aspects of reproducibility and reliability advocated so strongly and aptly by such researchers as Wagman and Pierce [1969]. This could not be accomplished in this case, but should be incorporated into the experimental design plans of others who intend to pursue the same goals.

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